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Characterization of a self-sustained, water-based condensation particle counter for aircraft cruising pressure level operation

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Abstract. Aerosol particle number concentration measurements are a crucial part of aerosol research. Vertical profile measurements and high-altitude/low~~–~~-pressure performance of the respective instruments become~~ more and~~ more important for remote sensing validation and as a key tool for the observation of climate variables. This study tests the new, commercially available, water condensation particle counter (MAGIC 210-LP) for the deployment at aircraft cruising pressure levels, that the European research infrastructure IAGOS (In-service Aircraft for a Global Observing System; www.iagos.org) is aiming for by operating measurement instrumentation on board~~ of~~ passenger aircraft. We conducted a series of laboratory experiments for conditions, which simulate passenger aircraft flight altitude ~~operations.~~operation pressure. We demonstrate that this ~~model~~type of water condensation particle counter shows excellent agreement with a butanol-based instrument used in parallel, and a Faraday cup aerosol electrometer serving as the reference instrument. Experiments were performed with test aerosols ammonium sulphate~~,~~ and fresh combustion soot~~ as well as ambient aerosol,~~ at pressure levels ranging from 700 hPa down to 200 hPa. For soluble particles like ammonium sulphate, the 50% detection efficiency cut-off diameter (D_{50}) was around 5 nm and did not differ significantly for all performed experiments. For non-soluble fresh soot particles, the D_{50} cut-off diameter did not differ significantly for particle sizes around 10 nm, whereas the D_{90} cut-off diameter increased from ~~17~~19 nm at 700 hPa to ~~34~~37 nm at 200 hPa. The overall counting efficiency for particles larger ~~30~~than 40 nm reaches 100% for working pressures of 200 hPa and higher~~. Though we observed a drop of the counting efficiency from 100% to 90% for particles smaller than 15 nm, as soon as we reached a pressure of 250 hPa. For pressure conditions down to 200 hPa, the counting efficiency for particles smaller than 15 nm dropped further and reached 80%. This feature, however, has only minor impact on the overall excellent performance of the instrument at all tested pressure conditions~~.

1 Introduction

Condensation Particle Counters (CPC) experienced a rise in ~~popularity~~use in recent years, driven by the ~~rising~~increasing awareness of the adverse effects that particles can have on~~ aspects such as climate change.~~ air quality, and public health, and all their interrelations (Von Schneidemesser et al., 2015). ~~Specifically, the monitoring of atmospheric aerosol (McMurry, 2000) including extreme conditions like measurements on airborne platforms (Petzold et al., 2013),~~Specifically, the monitoring of atmospheric aerosol on ground (McMurry, 2000) as well as on airborne platforms (Petzold et al., 2013), the measurement of exhaust aerosol from various sources (Giechaskiel et al., 2009; Petzold et al., 2011; Bischof et al., 2019), indoor aerosol (Salimifard et al., 2020), and airborne viruses in the still ongoing pandemic (Somsen et al., 2020) are current key applications of condensation particles counters.

A condensation particle counter (CPC) measures the aerosol particle number concentration by activating nanometre~~ size~~-sized particles in a supersaturated environment and further growing them to optically detectable droplets in the small micrometre size range. Single particles are subsequently detected and counted ~~by means of~~utilizing a photodetector measuring the intensity of the scattered radiation of a laser beam. John Aitken is known for his early experiments in which he started counting particles which had grown in an expansion chamber due to the supersaturation of water vapour~~,~~ ~~manually~~ (Aitken, 1888).

In general terms, the measurement principle of a CPC can be broken down into three steps: saturation by which a ~~supersaturated vapor~~saturated vapour of a working fluid is formed inside the CPC, supersaturation and subsequent condensation by which ~~the vapor~~vapour condenses on the particle, and detection, by which the enlarged particles scatter light when passing through a laser ~~which is then counted by a photo diode (Bischof, 2022).~~beam which is then counted with a photodiode, see, e.g. Bischof (2022); Hinds (1999); Cheng (2011)

~~By today~~Today, mainly three working fluids are in use, ~~namely~~ n-butyl alcohol (or n-butanol), water and isopropyl alcohol (2-propanol or isopropanol or for low pressure applications perfluoro-~~trybutylamine (FC43, Fluorinert).~~tributylamine can be used. For all working fluids, detection efficiency experiments have been conducted over a certain operation pressure range ~~(e.g.,~~ (e.g.Brock et al., 2000; Bundke et al., 2015; Gallar et al., 2006; Hermann et al., 2007; Williamson et al., 2018) which demonstrated the applicability of each working fluid for low-pressure operation CPCs. It should be noted that the use of both butanol and ~~FC43~~isopropanol is limited by the ~~facts~~fact that (1) ~~butanol is a~~both are flammable ~~liquid~~liquids and (2) ~~FC43 is a strong greenhouse gas~~can take up water at high humidity and only reach best performance at low pressure levels, whereas water has the advantage to avoid health and safety concerns of butanol. Disadvantageously, water has a three times higher mass diffusion coefficient ~~(Hering et al., 2005; Mei et al., 2021)~~ which increases the consumption of the working fluid during operation~~.~~ (Hering et al., 2005; Mei et al., 2021).

~~The~~Global aerosol observation is targeted by the European research infrastructure IAGOS (Petzold et al., 2015~~;~~ ~~www.iagos.org)~~) which aims to cover all essential climate variables of the atmosphere, including aerosol particles (Bojinski et al., 2014) by ~~means~~regular and global-scale measurements conducted on board of ~~regular and global-scale measurements conducted on board~~a fleet of ~~a fleet of~~ passenger aircraft equipped with automated scientific instrumentation. The IAGOS aerosol instrument using butanol-based CPC is described in detail by Bundke et al. (2015) and provided the first results during the observation of the Raikoke volcanic ash plume by IAGOS (Osborne et al., 2022)~~–~~. However, because of its flammability the ~~fact that~~use of butanol ~~is a flammable liquid, strongly hinders the operation of this type of instrument aboard~~on passenger aircraft~~.~~ requires special permission which we were unable to attain. Instead, the application of water-based CPCs is highly advisable, mainly under ~~considerations~~consideration of flight security aspects.

This study is part of the development of a new air quality ~~package~~instrument for IAGOS, in response to these flight safety aspects. ~~It comprises the measurements of the particle size distribution in the diameter range from 125 nm to 4µm by means of~~The package consists a modified Portable Optical Particle Spectrometer (POPS, ~~(Gao et al., 2016)~~Gao et al. (2016) originally developed by NOAA~~, of~~) which measures the particle ~~extinction coefficients at different wavelengths as well as~~size distribution in the ~~NO_2 concentration by means of~~diameter range from 125 nm to 4 µm; four Cavity Attenuated Phase Shift (CAPS, Kebabian et al. (2005); Kebabian et al. (2007) Aerodyne Research Inc., Billerica, MA, USA) instruments~~,~~ to measure the particle extinction coefficients at different wavelengths as well as the NO_2 concentration; and finally ~~of the total particle number concentration measured by~~ the water-based MAGIC 210-LP CPC to measure the total particle number concentration which is characterised in this work.

The new water-based condensation particle counter (MAGIC 210-LP; Moderated Aerosol Growth with Internal water Cycling – Low Pressure) for low~~-~~-pressure applications ~~characterized~~down to 300 hPa characterised in this study was recently

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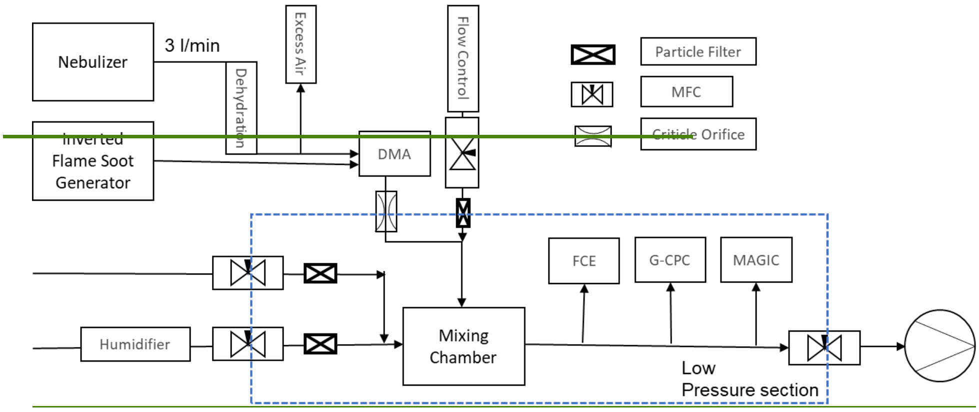
introduced into the market by Aerosol Dynamics Inc~~.,~~. and is based on the standard MAGIC CPC, which contains a pre-humidifier, where the aerosol sampling flow is guided to a continuous wet wick with different temperature zones. ~~Starting~~The humidified sample flow starts with the cold conditioner region, then the warm initiator and a cold moderator zone before finally passing the optics head (Hering et al., 2019). The MAGIC 210-LP CPC was subjected to counting efficiency experiments for a ~~broad~~ pressure range down to 200 hPa and ~~for~~ different types of test aerosol particles~~. The~~ representing salt particles and non-dissolvable particles. The conducted experiments were part of the qualification of the individual components of the new IAGOS ~~Air Quality Package under development~~air quality instrument.

2 Methods

A schematic of the experimental set-up is shown in Figure 1. ~~A brief summary of the experimental set-up is given here.~~To~~ A description with greater detail is provided in prior studies (Bundke et al., 2015; Bischof, 2022). In order to~~ provide a steady and constant particle production in size distribution and number concentration, a constant output atomizer (Model 3076, TSI Inc., Shoreview, MN, USA) was used, which nebulizes a constant stream of an ammonium sulphate (AS) solution (Liu and Pui, 1975); (TSI Inc. Model 3076 Manual). After the aerosol flow passes through a diffusion ~~dried~~dryer tube, the relative humidity reaches levels ~~of~~ below 5%. ~~It~~The sample flow follows a charging process by passing through a radioactive ~~AM~~Am-241 source and the classification in a monodisperse aerosol takes place by a Vienna-type Differential Mobility Analyzer (DMA, Model M-DMA 55-U, Grimm Aerosol Technik GmbH & Co. KG, Ainring, Germany). This aerosol enters the low-pressure zone by passing through a critical orifice. The aerosol is diluted within the ~~Mixing~~mixing chamber ~~where also the~~ with aerosol-filtered air. The pressure is controlled by a LabVIEW program ~~by means of~~through multiple mass flow ~~controller~~controllers with ~~an~~a PID approach. At 200 hPa, the measured standard deviation was less than 0.1 hPa with an integration time of 100 s. Furthermore, the relative humidity is actively controlled by adding a stable humidified air flow into the system through the mixing chamber, which is limited to ~~value of~~ approximately 30% relative humidity. Temperature, inline pressure, and relative humidity are measured in the mixing chamber. Water vapour can be added to test particle activation growth effects for different relative humidity levels. After passing the mixing chamber, the aerosol flow is provided to the measuring instruments using individual isokinetic, iso-axial samplers located in the centre of the sample line. ~~Here, a Sky-CPC 5.411 (Grimm) was used as a well~~ The diffusion losses are assumed to similar for all instruments. The flexible conductive sampling tubing length from the line to the instruments is set to 25 cm for instruments sampling at a flow of 0.6 l/min and adjusted proportionally to instruments with a different sampling flow. Here, a Sky-CPC 5.411 (Grimm) was used as a well-characterized butanol condensation particle counter (Bundke et al. 2015). An aerosol electrometer was used as a traceable reference instrument for particle counting measurements (FCE, Model 5.705, Grimm). The instrument ~~under characterization~~of interest was the newly developed Moderated Aerosol Growth with Internal Water Cycling CPC (MAGIC 210-LP, Aerosol Dynamics Inc, Berkeley CA, USA). For the fresh flame soot measurements, the nebulizer as well as the dehydration tube were replaced by a Miniature Inverted Flame Soot Generator (Argonaut Scientific Corp., Edmonton, AB, Canada). A description with greater detail is provided in prior studies (Bundke et al., 2015; Bischof, 2022).



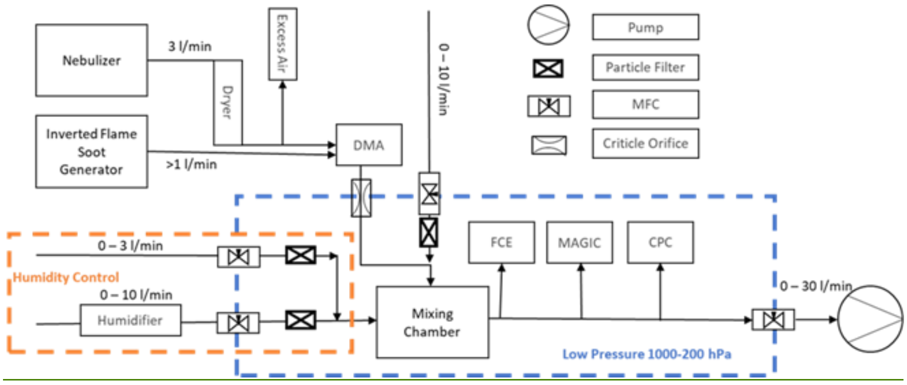


Figure 1. Flow schematic of the laboratory set up for the low-pressure characterization with two aerosol sources. The inline pressure is controlled via mass flow controllers (MFC); the aerosol size classification is ensured with a differential mobility analyser (DMA) ~~und~~and the faraday cup electrometer (FCE) functions as a reference instrument for particle counting).

The DMA was operated stepwise ~~with~~for 30 seconds for each voltage level corresponding to different ~~particles~~particle sizes starting at an upper limit of 140 nm and going down to 2.5 nm. To avoid transition effects and to achieve an equally ~~distributed~~sized aerosol inside all measuring instruments, the first 15 seconds for each particle size setting of the DMA were excluded from the dataset. Earlier experiments have shown that this time is sufficient to flush the system.

~~For best performance the~~The inverted flame soot generator was operated with an oxidation-air-to-propane ratio of 7.5 L/min air to 0.0625 L/min propane. This ensures~~ a~~ stable aerosol production with low organic carbon soot (Bischof et al., 2019; Kazemimanesh et al., 2018).

2.~~3~~1 Data analysis procedure

A major issue for the measurement of nanometre-sized particles arises from the use of a DMA as a size selector which is based on particle ~~using a DMA is~~ mobility and therefore the presence of ~~multiple~~multiply charged particles~~. These~~ needs to be accounted for when analysing electrometer counting statistics. The particles are ~~erroneous~~ selected according to their charge-to-size ratio by the DMA because they have ~~the~~ identical electrical mobility as singly charged particles ~~of the DMA~~

~~selected size~~ but are larger in size. ~~This effect leads~~These multiple charges lead to a notable difference in the counting rate between a condensation particle counter and an aerosol electrometer. To address ~~this artefact~~multiply charged particles biasing the concentration discrepancy, the correction scheme and routine ~~shown in Figure 3 which~~ was first introduced by Bundke ~~was used~~ (Bundke et al., 2015; Bischof, 2022). Further explanation is given in the SI.

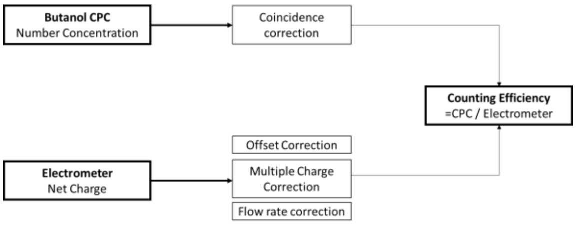
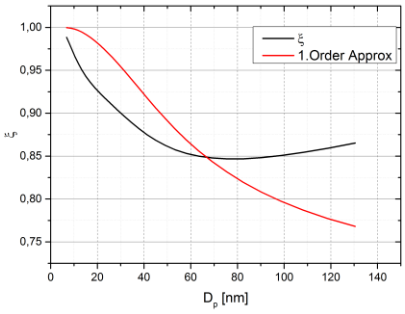


Figure 2. Flowchart of the data inversion procedure for particle concentration determination.

~~The Multiple charge correction can be expressed by~~

~~$N^*_{FEC} = \xi(D_p) N_{FCE}$ (Bundke et al., 2015),~~

~~as N^*_{FEC} as the corrected Electrometer number concentration and ξ as the calculated correction factor~~



~~**Figure 3. Multi charge correction function adapted from Bundke et al., (2015).**~~

~~Figure 3 shows the multi-charge correction factor ξ(Dp) as function of the particle diameter. The red line shows the first order approximation ignoring the actual size distribution. The first order approximation deviated significantly (up to 15%) from the ξ (D_p) curve. Thus, the actual size distribution measurement needs to be considered.~~

~~To give a more quantitative overview of the efficiency curves an~~An exponential fit function introduced by Wiedensohler et al. (1997~~)~~). Here, the revised formulation by (Banse et al., 2001) was used to give a more quantitative description of the particle counting efficiency curves compared to the electrometer.

Equation (1) $\eta = A - B * (1 + \exp$ ~~$\frac{(D_p - D_1)}{D_2})^{-1}$~~ $(\frac{(D_p - D_1)}{D_2}))^{-1}$

~~Here,~~where η is the counting efficiency, D_p is the particle size, and A, B, D_1, and D_2 are fitting parameters of this four-parameter exponential function.

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3. Results and discussion

The MAGIC -LP (Low Pressure) CPC ~~has~~is controlled by two variables which are critical for low~~-~~ pressure measurements. ~~One~~The first variable is the ~~overall~~ laser power which is adjusted to compensate for variations in droplet size as a function of the operating pressure. The second variable is the detection ~~offset~~threshold voltage which ~~was~~is adjusted to compensate for variations in background scattered light (i.e., measured light with zero ~~particles counts) as the laser power varies. The~~particle counts) as the laser power varies. When the internal pressure sensor is measuring a decreasing pressure, it increases the laser power to adjust the detector offset, until only the detector threshold is the only criterion for signal detection. In the experiments, the MAGIC 210-LP CPC was operated with the temperature settings recommended for low pressures by the manufacturer in the operational manual. During normal (ambient, 1000hPa) operation, the conditioner is maintained at 18 K below and the initiator at 17 K above the heat sink temperature, which is typically a few degrees above ambient. The moderator temperature is normally set as a function of input dew point to minimize water usage. The user has the option of changing this temperature or setting fixed temperatures. The manual for the MAGIC 210-LP states, that the conditioner temperature should be kept at 2°C and the moderator at 4°C for low~~-~~ pressure operations. The initiator is fixed at 45°C to remain below the boiling point when operating at pressures as low as 150 hPa. These working points, however, ~~could~~cannot not be reached ~~as~~if the heatsink exceeds temperatures of 33°C ~~during warmer surroundings.~~. During measurement a heatwave occurred, and it ~~becomes~~became clear, that the thermoelectrical devices get to their limits. It was then observed, that in case the temperatures of the conditioner and the moderator are about 3 K above their recommended ~~value~~values, the counting efficiency decreases by about 20% from 100% to 80% overall counting efficiency at pressure levels 250 hPa and below. ~~Furthermore, the slopes of the efficiency curves become less steep and the D_{50} increase up to 27 nm (34 nm) for AS respectively (soot).~~ This limitation, however, is solvable by maintaining the ΔT between all temperature zones of the sections of the growth tube equally.

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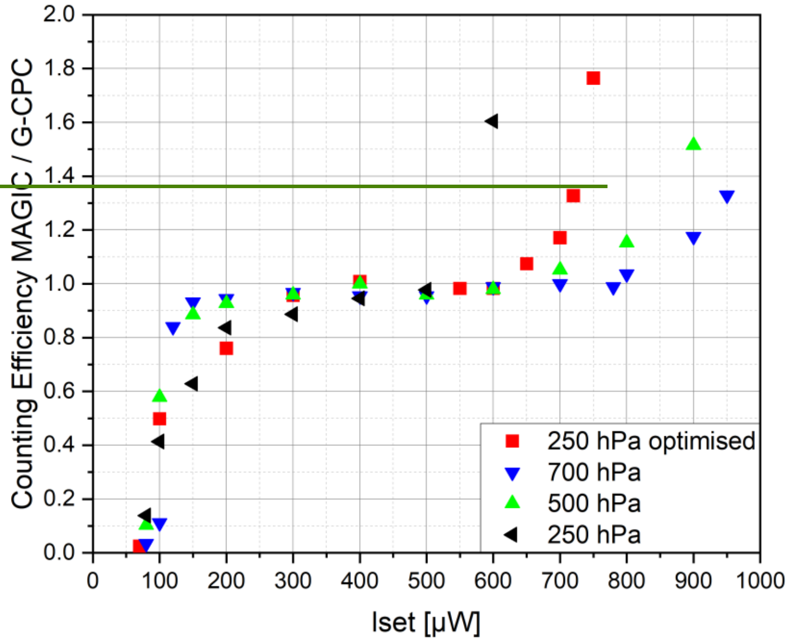

~~**Figure 4. Counting Efficiency response for different laser power**~~ Manufacturers **settings** ~~**(Lset) and pressure levels for 100 nm particles.**~~

~~As the absolute pressure during operation decreases thus, also the droplet growth resulting in smaller droplets to be counted. This is compensated by adjusting the laser power and the detector offset. The instrument firmware makes these adjustments automatically based on a lookup table, and the 1-sec averaged reading for the~~ were not optimised for operating pressure~~.~~ ~~Concentrations are reported with respect to laboratory conditions of 25°C and 1013 hPa.~~

~~Following Optimizations were applied. The MAGIC 210-LP was designed for operation at pressure levels as low as 300 hPa, but we were able to extend the operation~~ down to 200 hPa ~~by the following means: In Figure 2 the counting efficiency of MAGIC divided by G-CPC at different pressure levels for 100 nm particles is shown for a range of initial laser power settings.~~. For ~~example, at~~ 250 hPa ~~the laser power set point of 300 µW – is multiplied by a pressure dependent boost factor of approximately 6, resulting in 3630 µW, whereas the offset reaches 0 V. The additional stray light at such a~~, we found, that the required laser power was so high ~~powe, was more than the detector offset alone could compensate for, necessitating an increase of the~~ that the electronics were incapable of zeroing the baseline voltage. By adjusting the values for the laser power, detector threshold ~~from 250 mV as for the optimised Graph a threshold of 400 mV was set. A stable counting rate was obtained for set point at 500 µW for all pressure ranges. To ensure the same response for higher pressure levels the offset must be set to a high value of over 300 mV to compensate the higher threshold at ground pressure levels. The~~ and offset, we were able to expand the use of the MAGIC LP-210. Those values were then satisfying for the complete pressure range without manually changing these parameters ~~were always checked by comparing with the G-CPC as well with zero counting, when a particle filter was applied in front of the pressure line~~. Further explanation on this is given in the SI.

To give an overview of the two particle types we used for the evaluation studies, the aerosol size distribution for the test aerosol is shown in Figure 5.

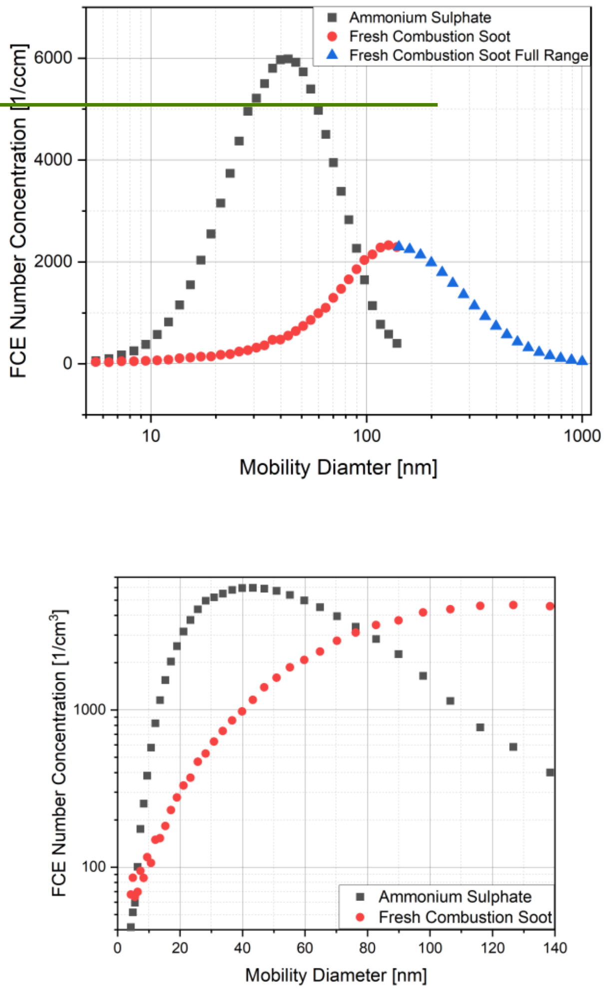

Figure 3. Particle size distributions were measured by Electrometer and sized by DMA for ammonium sulphate and fresh combustion soot. For this work, the particle mobility sizes were measured ~~till~~to 138 nm, so the size resolution at lower sizes is suitable for the cut-off characterisation. The full particle size distributions are available at (Weber et al., 2022).

~~The focus~~In order to achieve a high resolution for smaller particle sizes, we terminated at 138 nm mobility particle sizes, which corresponded to 3300 V. This value was ~~the~~satisfying to picture the ammonium sulphate size distribution, but this size restriction covered only parts of the fresh combustion soot size distribution.

The overall counting efficiency, the cut-off diameter and the linearity of the two condensation particle counters compared to the electrometer used as a reference instrument~~.~~ at different pressure levels was essential to look at for the instrument validation for IAGOS operation conditions. The measured particle concentrations were ~~being~~ compared to the ~~corrected~~ electrometer concentrations~~.~~ corrected for multiple-charged particles s. First, we demonstrate the overall efficiency of the instrument by using ammonium sulphate as a particle type. Ammonium sulphate is a common particulate matter compound in the atmosphere. Fresh combustion soot as a second aerosol type is of interest, because it may serve as a proxy for anthropogenic aerosol, and in particular, the MAGIC should be able to measure non-volatile particle matter emissions from aircraft engines while operating on IAGOS. In Figure 6, the particle size~~-~~-dependent counting efficiency of the G-CPC and the MAGIC 210-LP with respect to the ~~multicharged~~ multiple-charge-corrected ~~FEC~~FCE reference measurements are shown. To show a clear picture of the cut-off diameter, we do not show explicit data above 50 nm, since the instrument reaches a stable plateau of the counting efficiency. In Figure 7, the scatter plot ~~demonstrating~~demonstrates the overall linearity between the instruments.

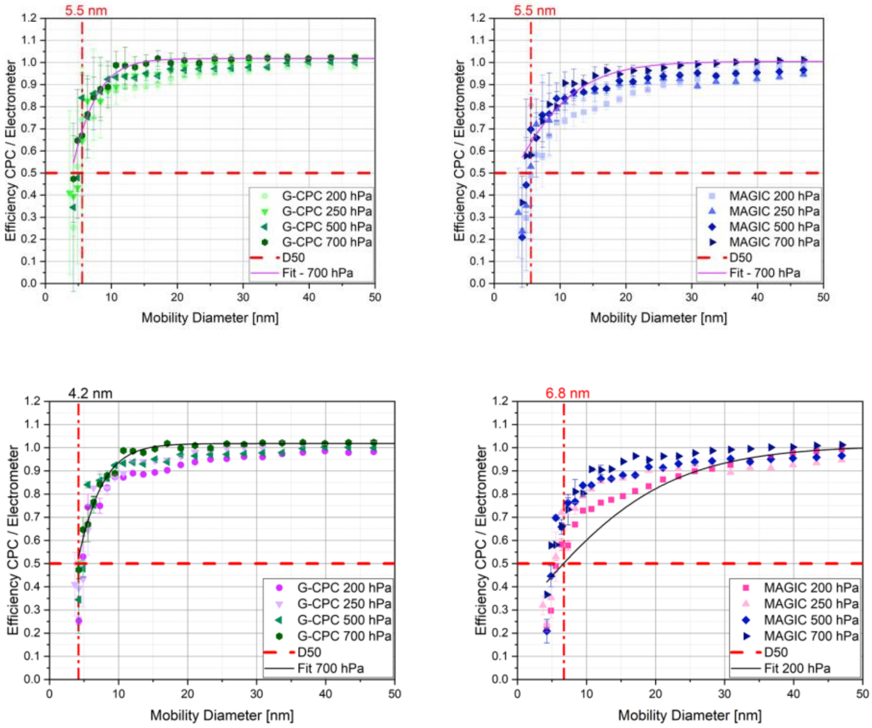

Figure 4. Compilation of the efficiency ratio curves of the Sky-CPC 5.411 (G-CPC) (left) and the MAGIC 210-LP CPC (right) to the FCE reference - at ~~difference~~different operation pressures as a function of the particle size using ammonium sulphate particles. The variance of the measurement is indicated by vertical bars.

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Using ammonium sulphate as a particle material, the instruments respond with an excellent agreement with the FCE reference instrument, with a slope of 1.0 ±0.05 regardless of the inline pressure. The MAGIC 210-LP and the Sky-CPC ~~stick~~

~~to~~scatter around the 1:1 ~~ratio~~line, showing ~~a ~~counting linearity for the full spectrum of particle concentrations~~ as shown in Figure 7~~.

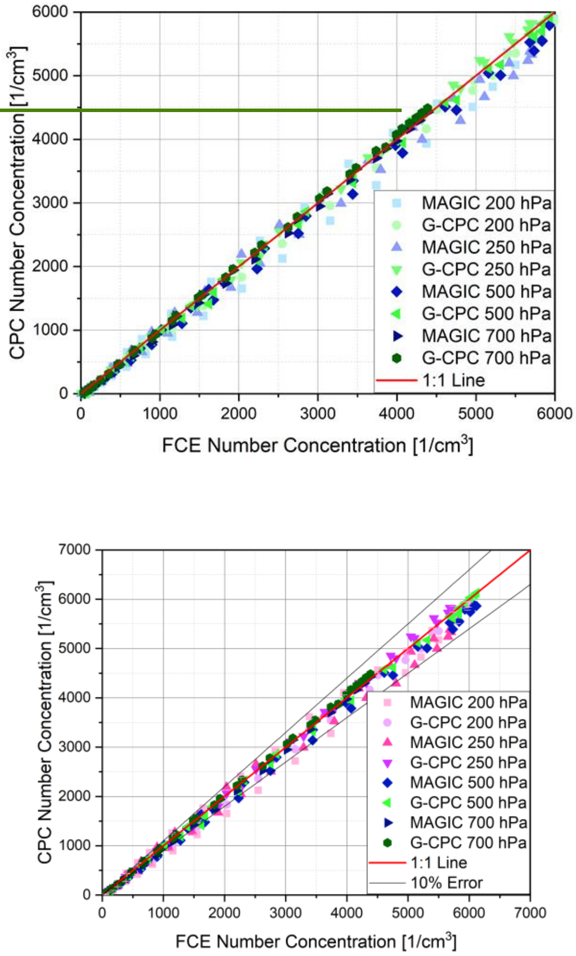


Figure 5. Comparison of the counting linearity between both CPC types and the Electrometer at different pressure levels for nebulized ammonium sulphate.

When looking deeper into the detail at ~~low~~small particle sizes, both CPCs ~~have~~show a D_{50} cut-off diameter of around 5 nm at all pressure levels~~.~~ (see Table 1~~)~~). The reported D_{50} ~~diameter ~~value is in accordance with previous measurements ~~done~~performed with the standard MAGIC ~~and ~~instrument, using ammonium sulphate as aerosol material (Hering et al., 2005). The G-CPC shows no major change in counting efficiency behaviour when it is operated at reduced pressures. The MAGIC 210-LP counts at least 90% of the particles when compared to the electrometer for pressure levels higher than 250 hPa and ~~for ~~particle sizes larger than ~~15~~30 nm. As the operation pressure reaches 200 hPa, the counting efficiency suffers from a small drop to about 80~~%~~%, but only for particles smaller ~~15 nm. For pressure levels higher 500 hPa the observed~~

~~efficiency is > 95% for all particles > 15 nm.~~ than 15 nm. The ~~parameters for the~~ laser power and detector threshold parameters were ~~choosen~~chosen to cover all pressures down to 200 hPa. ~~This drop in particle counting efficiency for small particle sizes would be negligible when using a large sampling line compared to a butanol CPC, since those particle does not reach the instrument anyway.~~

As a second particle type, we used combustion soot produced ~~by means of~~utilizing the Miniature Inverted Flame Soot Generator (Bischof et al., 2019). We used the second type to show the behaviour of an aerosol, that does not dissolve in a liquid. The experimental set~~-~~-up was therefore adjusted by replacing the nebulizer and its subsequent diffusion ~~drier~~dryer with the inverted flame soot generator.

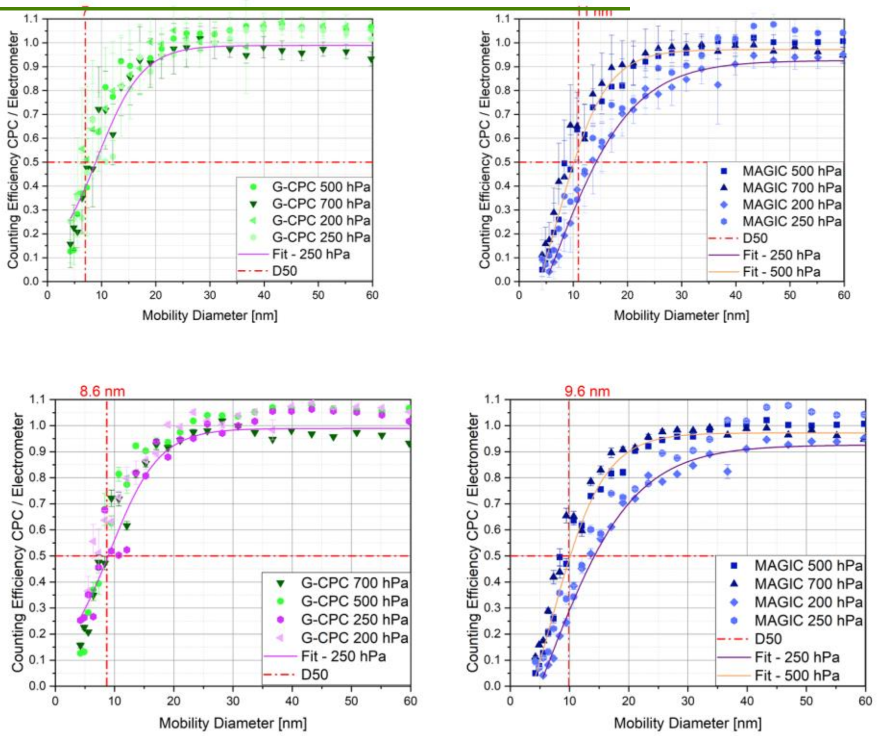
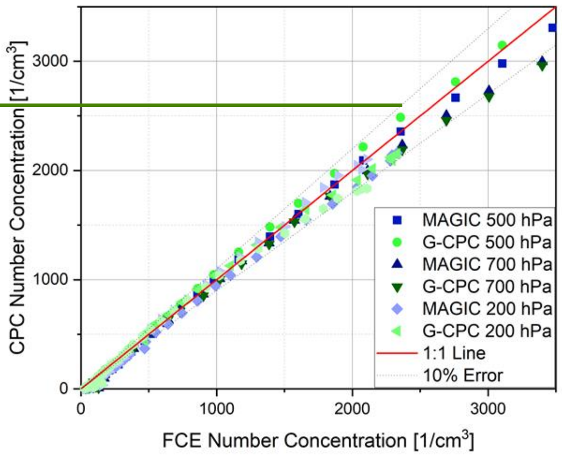


Figure 6. Comparison of the efficiency ratio curves of the Sky-CPC 5.411 (G-CPC) (left) and the MAGIC 210-LP CPC (right) to the electrometer reference at ~~difference~~different operating pressures as a function of the particle size using fresh combustion soot. The variance of the measurement is indicated by vertical bars.

Figure 8 and Figure 9 ~~shows~~show the comparison between the Grimm CPC, MAGIC 210-LP and Electrometer for the freshly generated combustion aerosol at different levels of operating pressure. The G-CPC and the MAGIC 210-LP show ~~a~~ nearly identical behaviour for counting efficiencies at pressures higher than 250 hPa. For lower pressure, the G-CPC continues to measure with the same efficiency. As ~~soon as an ambient~~with a gradual shift with decreasing pressure ~~of~~to 200 hPa ~~is reached~~, the D$_{50}$ cut-off of the MAGIC 210-LP ~~increased~~increases to around 15 nm and its D$_{90}$ to about 40 nm. ~~For operation in the IAGOS infrastructure, the corresponding D$_{50}$ at 250 hPa of 10 nm and D$_{90}$ of 25 nm seem suitable as particles smaller~~

~~15 nm will not pass the inlet line to the instruments, yet the overall uncertainties must be estimated by comparing in actual flight measurements with MAGIC 210-LP and G-CPC~~.



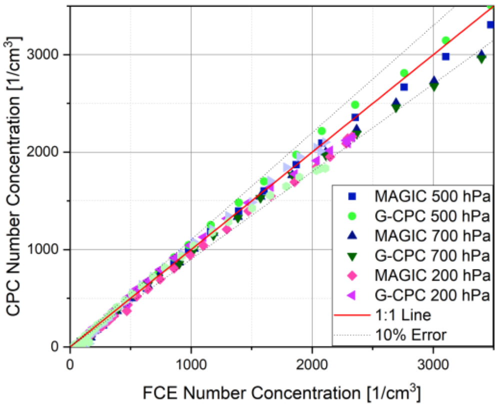


Figure 7. Comparison of the counting linearity between CPC and Electrometer at different pressure levels for fresh combustion soot.

As ~~a~~an insoluble hydrophobic substance, fresh combustion soot is not activated for droplet formation inside a CPC as ~~efficient~~efficiently as hydrophilic substances (Petzold et al., 2005). Therefore, soot particles need to be larger in diameter for nucleus activation than hydrophilic particles, which explains the increase of the D_{50} compared to our ammonium sulphate experiments. For ~~aviation~~airborne measurements, it is unlikely to encounter fresh combustion soot, ~~but it~~whereas measurement campaigns and IAGOS flights targeting fresh combustion soot in common flight corridor routes. Furthermore, fresh combustion soot is a good proxy for non-hydrophilic substances.

~~As the Table 1 gives an overlook over linearity of the particle condensation instruments towards the electrometer counts, the Person Rate r² never fall below 0.99. As regards the instrument linearity for soot particles, the MAGIC 210-LP as well as the Sky-CPC show up to 15% less particles compared to the FCE with increasing total number concentrations. This might be an artefact caused by the multiple charge correction underestimating multiply charged particles. A possible reason for this is that the multiple charge correction is based on the size distribution measurement, which for soot could only be measured partially using the m-DMA, so that the log normal fit applied to the measurement data might underestimate the right tail of the distribution resulting in an underestimation of multiply charged particles. We aimed for a high size resolution for particle sizes smaller 30 nm for a precise cut-off efficiency determination.~~

~~Looking at the D_{50} Value of Table 1~~Tables 1 and 2 give an overview of the counting linearity of the CPC type instruments with respect to the FCE reference instrument, for both aerosol types. The Pearson correlation coefficient r² never drops below 0.99 for each measurement. With respect to the instrument linearity for soot particles, the MAGIC 210-LP as well as the Sky-CPC underdetermine particle number concentration by up to 15% compared to the FCE with increasing total number concentrations at 700 hPa. However, this effect was not observed for the other pressure ranges. The average counting efficiency for the 700 hPa trials is still within the overall uncertainty (10%) (Petzold et al., 2011) for all counting efficiency measurements; see parameter A in Table 1 and 2 for details.

Looking at the D_{50} value in Tables 1 and 2, both Instruments ~~have the same range of particle~~ show a cut-off diameter ~~of~~close to 5 nm~~, where only 50% particle detection could be archived towards the reference instrument~~ for ammonium sulphate. This agrees with the reported detection limit for both instruments from the manufacturer and publications (Hering et al., 2014; Bischof, 2022).

When looking deeper into the cut-off efficiency measurements, the overall trend for the MAGIC 210-LP becomes obvious. With decreasing pressure, the ~~delta~~difference between D_{50} ~~to~~and D_{90} is increasing, resulting in a less steep ~~decreasing of~~decrease in the counting efficiency towards smaller particle sizes. ~~Thus, resulting in~~This feature then causes a higher uncertainty for ~~measuring~~ measurements of the total number concentration ~~involving the~~of an aerosol with a strong Aitken mode, particularly for low-pressure surroundings. Whereas the D_{50} value does not change significantly, the D_{90} increases significantly. The overall large ~~delta~~difference between D_{50} ~~to~~and D_{90} indicates a shallow ~~decreasing of~~decrease in counting efficiency over a wide particle size range. Switching the particle type to soot, the lower size detection limits increase, because of ~~the~~its less efficient activation ~~affinity of this particle type~~.

Table 1. **Coefficients of the Exponential Fit of the Counting Efficiency Curves for the Sky-CPC 5.411 (G-CPC) and the MAGIC 210-LP CPC and ~~slopes~~ for different line pressure values and ammonium sulphate.**

Instrument	Line Pressure	~~Slope~~	A	B	D_1 [nm]	D_2 [nm]	~~Derived~~Equation calculated D_{50} [nm]	Exp. D_{50} [nm]	~~Derived~~Equation calculated D_{90} [nm]
G-CPC	200	~~1.03±0.02~~	0.96	2	2.8	1.8	4.9	4.8±0.7	9.1
MAGIC 210-LP	200	~~0.98±0.01~~	1.03	1.7	0.1	8.1	6.8	5.5±0.8	20.9

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G-CPC	250		1.~~02±~~0~~.01~~	~~1.0~~	2	1.7	2.6	4.6	5.5±0.8	9.4
MAGIC 210-LP	250		0.~~95±0.02~~97	~~0.97~~	2	1.6	3.4	5.5	5.5±0.8	12.9
G-CPC	500	~~1.00±0.01~~	0.98		2	3.0	1.4	4.6	5.5±0.8	7.5
MAGIC 210-LP	500		0.~~97±0.01~~95	~~0.95~~	2	2.5	2.2	5.2	5.5±0.8	10.6
G-CPC	700	~~1.02±0.02~~	1.0		2	1.5	2.5	4.2	4.3±0.7	8.9
MAGIC 210-LP	700	~~1.01±0.01~~	1.0		2	0.1	4.1	4.6	4.3±0.7	12.3

~~Analyzing the behaviour of the fitting parameter a, which can be compared to the slopes, since it represents the plateau of the fit function, and the derived parameter D_{50} of the fitting function in Table 1, no clear trend seems to be visible. D_{50}, which is the counting efficiency, where only half of the particles could be detected as the exponential fit suggested, is close to 5 nm for both condensation particle counters and fits the experimental data. This agrees with the estimated detection limit from the experimental data.~~

Table 2. Coefficients of the Exponential Fit of the Counting Efficiency Curves for the Sky-CPC 5.411 (G-CPC) and the MAGIC 210-LP CPC for different line pressure values and fresh combustion soot.

Instrument	Line Pressure	~~Slope~~	A		~~Bb~~B	D_1 [nm]	D_2 [nm]	~~Derived~~Equation calculated D_{50} [nm]	Exp. D_{50} [nm]	~~Derived~~ Equation calculated D_{90} [nm]
G-CPC	700		0.~~84±0.01~~92	~~0.92~~	1.2	5.9	3.2	8.0	7±1.0	19.0
MAGIC 210-LP	700		0.~~86±0.01~~93	~~0.93~~	1.4	5.9	3.6	8.7	9±1.3	19.7
G-CPC	500	~~0.98±0.01~~	1.02		2	3.6	3.8	7.6	8±1.0	14.2
MAGIC 210-LP	500		0.~~95±0.01~~97	~~0.97~~	2	3.6	5.2	9.6	9±1.3	21.0
G-CPC	250		0.~~95±0.01~~99	~~0.99~~	0.94	9.2	4.2	8.6	7±1.0	19.1
MAGIC 210-LP	250		1.03~~±0.01~~	~~1.03~~	2	3.3	8.9	11.9	11±1.4	27.6

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G-CPC	200	~~0.95±0.01~~	1.01	1.03	6.6	4.2	6.7	5.5±0.8	15.9
MAGIC 210-LP	200	~~0.94±0.01~~	0.93	2	3.8	7.6	13.4	13±1.5	35.7

~~In Table 1 and 2 using the fitting parameters to compare with the slopes and the D50 derived from the formular and read in the experimental data., the values agree within the error margin. Showing, that the counting efficiency for line pressures of 250hpa is around 100%. The derived values of the fitting of D50 agrees within the uncertainty the experimental data. The Fitting curve is a function of the particle diameter. When the Fitting is right both derived parameters should fit.~~

Analysing the behaviour of the fitting parameter A, which represents the plateau of the fit function and can, and the derived parameter D_{50} of the fitting function in Tables 1 and 2, no clear trend is visible for the two aerosol types and instruments. The values of D_{50}, deduced from the fitting curves are close to 5 nm for both condensation particle counters and all pressure levels in case of ammonium sulphate (Table 1) and fit to the experimental data. For fresh combustion soot (Table 2), D_{50} values for the G-CPC instrument are slightly larger at a value of 8 nm, while for the MAGIC 210-LP the increase in D_{50} compared to ammonium sulphate is more pronounced. Overall, the agreement between values derived directly from the experiment and values deduced from the fitting procedure is within the error margin of the individual mobility size.

At lower pressures, the particle counting efficiency drops for small particle sizes in the Aitken mode range and below. Because of particle line losses during sampling, this performance, however, does not impact the quality of the measurements when using a sampling line of more than 1 meter length, as will be the case in applications aboard passenger aircraft equipped with IAGOS instruments. Here 50% (85%) of 5 nm (13 nm) particles will penetrate to the instrument (at 150 hPa, and 2.4 L/min total flow) (Bundke et al., 2015). In such a set-up, particles smaller than 13 nm in diameter will be removed by diffusion during the sampling process. Yet, the overall uncertainties must be determined by modelling the instrument responses of MAGIC 210-LP and G-CPC for different aerosol size distributions, mainly with and without a nucleation mode, for IAGOS – characteristic sample line lengths.

4. Conclusions and recommendations

The MAGIC ~~210-LP~~ CPC was recently introduced as a new water-based CPC with excellent overall performance compared to a standard Butanol CPC~~.~~ (Hering et al., 2014; Hering et al., 2019). In this work, we characterised a modified "LP" (Low Pressure; Version: MAGIC- LP 210) model of that water-based CPC design for flight altitude pressure levels as low as 200 hPa. We recommend~~, to test~~ testing each unit for low~~-~~ pressure applications and ~~adjust~~adjusting the manufacturer settings~~,~~ when operating at pressures lower than 500 hPa~~.~~ if necessary. When operating above this pressure level, the factory settings were satisfactory. We were able to have a look at 5 units to verify this was not an artefact of a single unit. Critical for a high counting efficiency ~~is~~are the laser power, detector offset and detector threshold. ~~-~~It is noted that since this study, the manufacturer has acted on the insights from this work and modified the firmware and design of the MAGIC 210-LP we tested to improve the performance at high ~~altitude and to better accommodate the automatic~~altitudes. Automatic adjustments in the laser and detector settings with operating pressure were incorporated in the newest model MAGIC 250-LP.

The MAGIC 210-LP operates ~~without loss in performance~~ at all pressure levels tested and reports reliable particle concentrations with overall detection efficiencies close to 100~~%. It's well engineered~~% for particles larger 40 nm. For the

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continuous operation on IAGOS aircraft packages, its water recycling mechanism makes the instrument attractive as well for long-term operation ~~at~~in harsh conditions with no or only very limited opportunities for instrument access and maintenance. To evaluate the instrument performance, and in particular, the counting efficiency, as a function of the aerosol type and pressure, an aerosol electrometer and a butanol condensation particle counter were used as established reference instruments. For ammonium sulphate particles, the MAGIC 210-LP CPC shows ~~an~~ excellent stability of the D_{50} cut-off diameter~~,~~ and overall linearity with an r^2 of 0.99. ~~Approved~~Verified by experimental data and an exponential fitting function, the overall counting efficiency reaches 100% for pressure levels higher than 200 hPa and particles larger than 30 nm, regardless of the particle type. However, at 200 hPa the counting efficiency for particles smaller than 30 nm drops notably to 90% compared to the electrometer or the butanol CPC. When the MAGIC 210-LP is exposed to a hydrophobic and insoluble particle type like fresh combustion soot, the water condensation particle counter shows similar behaviour for almost all particle sizes down to 30 nm for ambient pressure levels down to 250 hPa ~~when comparing~~ the ~~overall~~ linearity ~~stay~~is within 95%. This pressure range covers the operational conditions present during IAGOS aircraft flights. For pressures ~~below~~down to 200 hPa, the efficiency of the MAGIC 210-LP ~~is able to reach~~reaches 100% linearity towards the reference instrument for a large particle range. For particles smaller than ~~30nm~~30 nm the counting efficiency is lower than 90 %, decreasing to 70% (60%) for 20 nm (15nm) particles. Because of the reduction of the counting efficiency for particles smaller than 30 nm for operational pressure levels below 250 hPa, the uncertainty of the reported number concentration is enhanced, particularly when sampling an aerosol with a strong nucleation mode~~. The~~, and the lower counting efficiency of the MAGIC 210-LP for smaller particle sizes results in a higher uncertainty of the total particle count~~, that could be estimated by a side-by-side compassion during a continuous flight operation~~.

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Contributions of co-authors. PW performed all instrument calibrations, the instrumental set-up, and the data analysis. UB and BF designed the LabVIEW environment of the experimental set-up. MB helped during instrument preparations. SS, GL, and SH provided technical details of the instrumentation. PW, OB, UB and AP contributed to the manuscript and the interpretation of the results.

Conflict of interest. GL and SH are owners of, and SS is an employee of Aerosol Dynamics Inc, which developed and sell the MAGIC 210-LP. The other authors declare that they have no conflict of interest.

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